

LUNAR EXOSPHERE DURING ACTIVITY OF MAIN METEOR SHOWERS. A. A. Berezhnoy¹,¹Sternberg Astronomical Institute, Universitetskij pr., 13, Moscow, 119992 Russia

Introduction: The atoms and ions found in the lunar exosphere come mainly from the interactions of solar photons and solar wind with the lunar regolith. However, micrometeorite bombardment can also be an important contributor during main meteor showers and on the night side of the Moon. In this work the velocity distribution and the column densities of metal atoms associated with meteoroid impact are estimated. A technique for the spectroscopic study of species of impact origin is proposed. The connection between photolysis of impact-induced molecular species and the isotopic composition of the lunar regolith is also examined.

Physics and chemistry of collisions between meteoroids and the Moon: Meteoroids from the main meteor showers typically strike the Moon with velocities between 35 and 70 km/s. These impacts vaporize both the meteoritic matter and some of the target material. After the impact, the Moon captures a part of the ejected material.

Thermodynamic calculations based on quenching theory [1] were conducted in order to estimate the chemical composition of the fireball as it cooled to the point where chemical reactions effectively stopped. The initial fireball temperatures and pressures were set equal to $T_0 = 10000$ K and $P_0 = 1000$ bars, respectively. The fireball is assumed to cool adiabatically. The elemental composition of the fireball was taken to be that of a mixture of 10 % of CI chondrites and 90 % of the lunar regolith by mass. Specifically, it was assumed that chemical reactions end when two quantities, the chemical and hydrodynamic time scales became comparable. For a typical meteorite size of about 10^{-4} - 10^{-5} m [2], the hydrodynamic time scale is 10^{-8} - 10^{-9} s at the assumed fireball expansion speed of about 10 km/s. Quenching of the main reactions in the fireball occurs at $T_q \sim 3000$ - 4000 K and $P_q \sim 30$ - 100 bars [3].

Thermodynamic calculations of the fireball equilibrium chemical composition were performed for different temperatures and pressures. At quenching, the main O-, Si-, H-, Na-, K-, Ca-, S-, C-, N-containing species are SiO_2 , SiO , CaOH , Ca(OH)_2 , Na, K, CaO, SO_2 , CO_2 , NO, and N_2 , respectively, if no condensation occurs. If equilibrium condensation takes place then the main species are NaOH, O_2 , SiO_2 , SiO , NaOH, H_2O , Na, NaO, KOH, K, KO, Ca(OH)_2 , CaOH , CaO, SO_2 , SO, CO_2 , CO, N_2 , and NO. Zn and Cu are present as atoms in the gas phase at reasonable temperatures and pressures. Sulfur persists in the gas phase when the chemical composition quenches because the formation of solid FeS is kinetically prohibited [1].

Characteristics of the lunar exosphere during Perseid meteor shower: If all elements are delivered to the exosphere by the same effective

mechanism than we expect proportionality between atomic metal abundances in the lunar exosphere and elemental abundances in the regolith. Earth-based spectroscopic observations of the lunar atmosphere, however, do not indicate the presence of Si, Al, Mg, Ca, or Fe, which are major constituents of the regolith [4]. Therefore, the atoms of these refractory elements are not delivered to the exosphere by the same mechanisms valid for Na and K atoms.

In modeling meteoroid impact we choose parameters for the Perseid meteor shower because among the main meteor showers, the Perseids last longest and should therefore generate the largest effects. Specifically, we adopt the following parameters of the shower: the mass flux is 0.28×10^{-17} $\text{g cm}^{-2} \text{ s}^{-1}$; the mean impact velocity is 59.4 km/s [6]. The corresponding values for sporadic meteors are 6.34×10^{-17} $\text{g cm}^{-2} \text{ s}^{-1}$ and 16.9 km/s, respectively [7]. While the mass flux of sporadic meteors is in about 20 times higher than that of Perseids, vaporization and release of species to the exosphere occurs intensively only for high impact velocities (> 20 km/s). For example, a bright Na spot of lunar origin in the anti-lunar direction was detected after maxima of Perseid and Leonid meteor showers in 1998, but was not at other times [8]. Also, K atoms were not detected, which suggests that the typical velocities of K atoms produced during meteoroid impacts are less than escape velocity from the Moon, 2.4 km/s.

Let us apply the model of estimation of column densities of impact-induced exosphere [5] for the case of the lunar exosphere. Lifetimes of Na and K atoms in the exosphere are taken to be Na and K photoionization times [9], respectively, while Ca, Si, Al, and Fe lifetimes are taken to be equal to their ballistic flight times. CaO, SiO, AlO, and FeO photolysis lifetimes were taken from [5]. Estimated column densities of Na, K, Ca, Si, Al and Fe atoms on the Moon during activity of Perseid shower are 10^8 , 10^7 , 10^8 , 10^8 , 2×10^7 , and 10^7 cm^{-2} , respectively. These values are only upper limits because condensation of metal-containing species to the solid phase during hot cloud expansion was not considered. The estimated Ca column density is comparable with the Ca upper limit on the Moon (9×10^7 cm^{-2} [4]) while the estimated Si, Al, and Fe column densities are too low for detection by current telescopes. Estimated column densities of impact-produced Na and K atoms are equal to several percent of the total column densities of these atoms.

The energy of these atoms (about 0.3 eV) is higher than the average energy of majority of lunar Na and K, about 0.1 eV, desorbed from the regolith by solar photons. Typical height scales of impact-produced Na and K atoms are about 700 and 400

km, respectively. For these reasons impact-produced Na and K atoms can be detected at the middle lunar exosphere, at preferable altitudes of about 1000-2000 km. Na and K atoms of the meteoroid impact origin can be distinguished from the atoms of the solar wind sputtering origin by performing of spectral observations of the lunar exosphere during activity of main meteor showers and with the Moon inside the magnetosphere.

The photodissociation of NaOH, NaO and KOH, KO may be responsible for presence of hot Na and K atoms in the lunar atmosphere. From a comparison of ballistic flight times ($\sim 10^3$ s) and NaOH, NaO photolysis lifetimes (10 and 40 s [10]) it is clear that a significant fraction of the Na atoms produced during meteoroid impact can be delivered to the lunar atmosphere through photolysis of NaOH and NaO. The velocity distribution of such Na atoms is estimated from the solar flux [9] and NaOH, NaO photolysis rates [10]. We assume that kinetic energy of NaO and NaOH molecules before photolysis is negligible in comparison to the kinetic energy of the products of this reaction and that after photolysis 50 % of the excess energy is converted to the kinetic energy of Na atoms. The velocity distribution of the Na atoms produced through photolysis is non-Maxwellian; the average velocity of such atoms is close to the escape velocity from the Moon (see Fig. 1). Let us assume that the energies of K atoms produced through KO and KOH photolysis are the same as energies of Na atoms produced through NaO and NaOH photolysis because KO, NaO and KOH, NaOH dissociation energies, dipole moments, and electronic structures are comparable. Then only about 10 % of K atoms produced during meteoroid impacts will escape the Moon in comparison with 50 % Na atoms, this difference can explain the absence of K tail after Leonid meteor shower [8].

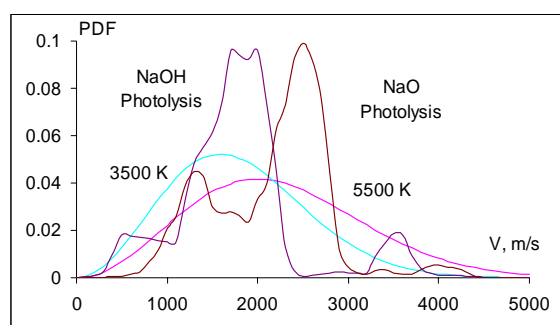


Fig. 1. Velocity distribution for Na atoms formed by NaO and NaOH photolysis and for Maxwellian distributions at 3500 and 5500 K.

Isotopic fractionation of the lunar regolith during meteoroid bombardment: The velocity distribution of S atoms produced by SO, SO₂ photolysis were also estimated with the same assumptions as for NaO and NaOH photolysis. The mean energies of the S and K atoms produced

through photolysis are comparable to the typical energies of S and K atoms in the hot cloud, about 0.25 eV. Enrichment factors of ³⁴S and ⁴¹K isotopes remained on the Moon after photolysis of SO, SO₂, KOH, and KO are estimated as 9, 7, 4, and 3 ‰. These values are too low to explain the enrichment of lunar S in ³⁴S and ⁴¹K isotopes in the fine size grain fraction of the returned samples, 10-20 ‰ [11] and 10-15 ‰ [12], respectively.

Using excess energy of solar photolysis products [10] we estimate average velocities of C, O, N, and N atoms produced through photolysis of CO₂, CO, O₂, NO, N₂ as 4.7, 5.2, 3.4, 4.3, and 5.9 km/s, respectively. Thus, majority of products of photolysis will escape from the Moon. For detailed study of isotopic fractionation of C, O, N caused by photolysis we need to know the velocity distribution of photolysis products.

For careful study of the influence of molecular photolysis on isotopic fractionation of Zn, Cu, Fe, Si, Mg, and Ca, theoretical and experimental studies of photolysis cross sections of hydroxides and oxides of these elements are required.

Conclusions: Based on quenching theory, the chemical composition of gas-phase species released to the lunar exosphere during meteoroid impacts has been estimated. The column densities of atoms of main elements in the exosphere during activity of Perseid meteor shower are estimated. In searching for impact-produced Na, K, and Ca atoms in the lunar exosphere, it is better to make spectral observations during activity of the main meteor showers at altitudes of about 1000-2000 km. Very high-resolution spectral observations would also be highly desirable for detection of non-Maxwellian velocity distribution of Na atoms produced by NaOH and NaO photolysis.

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References: [1] Berezhnoy A. A. et al. (2003) *PASJ* 55, 859-870. [2] Bruno M. et al. (2006) *MNRAS* 367, 1067-1071 [3] Berezhnoy A. A. (2007) *LPSC* 38, 1047 [4] Flynn B. C., and Stern S. A. (1996) *Icarus* 124, 530-536. [5] Berezhnoy A. A., and Klumov B. A. (2008) *Icarus*, in press. [6] Barbieri C. et al. (2001) *Earth, Moon, and Planets* 85-86, 479-486. [7] Gault D. E. et al. (1972) *Proc. 3th Lunar Sci. Conf.*, 2713-2734. [8] Smith S. M. et al. (1999) *GRL* 26, 1649-1652. [9] Huebner W. F. et al. (1992). *Astrophys. Space Sci.* 195, 1-289, 291-294. [10] Self D. E., and Plane J. M. C. (2002). *Phys. Chem. Chem. Phys.* 4, 16-23. [11] Thode H. G., and Rees C. E. (1979) *Proc. 10th Lunar Sci. Conf.*, 1629-1636. [12] Church S. E. et al. (1976) *Proc. 7th Lunar Sci. Conf.*, 423-439.